PROBLEMY KOLEJNICTWA
RAILWAY REPORT Issue 197 (December 2022)
IK INSTYTUT KOLEJNICTWA
DOI: 10.36137/1972E
ISSN 0552-2145 (print) ISSN 2544-9451 (on-line)

Evolution of Electric Traction Vehicle Design Based on the Example of Škoda Locomotives

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Summary

The article describes the evolution of Škoda electric locomotives, starting with vehicles supplied with 3 kV DC and 25 kV 50 Hz, initially featuring a resistor start-up (for DC supply), optionally high-voltage voltage regulation (for AC supply), and later with a pulse (thyristor) start-up. The railway network in Czechoslovakia was initially electrified with direct voltage (including the Prague junction); however, learning the advantages of the 25 kV 50 Hz voltage developed in Germany led to some new sections of the ČSD network being electrified with alternating current. At the same time, Czechoslovakia's national manufacturer Škoda developed vehicles (locomotives, EMUs) suitable for DC and AC operation. Initially, these were single-system vehicles, as the development of multi-system ones was technically complicated at the time (only short-series production was practiced). The advent of pulse-starting traction motors not only provided more economical and simpler traction motor control but also simplified the construction of multi-system vehicles. The article discusses the specifics of both engine start-up systems and the evolution of DC and AC vehicle design and operation.

Keywords: locomotives, Škoda, electric motor start, thyristor, transistor, GTO, IGBT, ČD, ŽSR, ČSD

1. Introduction

In Czechoslovakia, the electrification of railway lines, ongoing even before the Second World War, led to a demand for electric vehicles powered by direct current. The choice of 1.5 kV DC was due to the simplicity of using such a voltage, among other reasons. The vehicles ordered by the Czechoslovak railways were manufactured by Škoda. This continued after 1945, with Škoda remaining the main supplier of electric locomotives, designing and manufacturing locomotives powered by 3 kV DC, and later also 25 kV 50 Hz AC, as well as dual-system (3 kV+25 kV, 3 kV+15 kV) locomotives, though initially a very successful Swiss-made was used, designated by the ČSD as E499.1. Vehicles were manufactured both for the ČSD and for export (SZD, BDZ, DR, PKP). The early 1980s saw the emergence of locomotives with pulse-starting traction motors, and these are now standard on SŽ and ŽSR routes.

2. Electric motor start-up methods

An electric motor start-up may utilize a DC supply in the case of a resistor start-up (by including a resistor in the circuit) or take the form of a pulse start-up. The latter is considered more modern and more economical, although more technically complex.

2.1. Resistance start-up

One way of starting an electric motor, especially when supplied with a voltage > 100 V, is to regulate the current value using a resistor or resistors in series in the circuit [1]. A direct voltage supply is not possible due to the danger of the commutator sparking at high voltages. Resistors incorporated in series reduce the voltage flowing through the motor while the current remains unchanged, making the motor start smoother. The relationship between current, voltage, and resistance is defined by formulae 1–4:

$$I = \text{const.}, \tag{1}$$

$$U = U_1 + U_2 + U_3, \tag{2}$$

$$IR = IR_1 + IR_2 + IR_3, \tag{3}$$

$$R = R_1 + R_2 + R_3, \tag{4}$$

where: I – current, U – voltage, R – resistance.

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In other words, the motor requires a high current and a low voltage to start, which is achieved by resistors connected in series. Resistance start-up is the oldest DC electric motor start-up method, characterized by soft speed control by varying the supply voltage, while the change in rotor direction is achieved by changing the poles of the supply current. The advantage of the DC motor, apart from simple control, is that it can also be powered – via a rectifier – at 16.7 Hz or 50 Hz AC.

At start-up, the motors are connected in series directly to the overhead line, and the voltage is controlled by adjusting the resistance of the start-up resistor. As the number of turns of the motors' rotors increases, subsequent resistors are disconnected and, using contactors, the motors transition from a series connection to a parallel connection (which is done by disconnecting the bridge contactor). Energy losses during resistance start-up (and possibly resistance driving) are determined by the relationship described below (equation 5).

$$W = P \cdot t = U \cdot I \cdot t = I^2 \cdot R \cdot t, \tag{5}$$

where: I – current, U – voltage, R – resistance, t – time, P – power, W – work.

Thus, it is advisable to keep resistor driving to a minimum and to start the motor at maximum intensity – this makes it possible to reach the economic stage in the shortest time. As the rotor speed increases, the current decreases, so to maintain or increase the rotor speed, the contactors disconnect subsequent resistors and achieve resistance-free operation at a certain point. There are several types of resistance start-up – both for DC and AC motors:

1. AC wound-rotor motors – during start-up, the resistors between the rings feeding the rotor are switched on. As the rotor reaches its nominal speed, the resistors are disconnected by shorting the rings.
2. DC series motors – the resistors are incorporated into the circuit in series with the motor. Starting is achieved by changing the resistance of the resistor; an increase in resistance decreases the rotor speed while a decrease in resistance increases it, with I = const.
3. DC shunt motors – a resistor is also incorporated in series in the armature circuit, where the starting current is 10–30 times the nominal current, so to avoid damaging the motor or overloading the overhead line supply, the voltage is reduced while maintaining the current by including a resistor (known as a starter) in the circuit, among other things.

Rotor speed control is therefore based on connecting or disconnecting successive resistors, and electropneumatically controlled contactors are used to avoid current spikes. For more economical power consumption, the excitation of the traction motor magnetic field is reduced. As the speed of the rotors increases, it is more advantageous for the motors to transition from series to series-parallel or parallel (significantly decreasing energy loss due to lower resistance). The relationship between voltage, current and resistance for a parallel connection is defined by formulae 6–9:

$$U = \text{const.}, \tag{6}$$

$$I = I_1 + I_2 + I_3, \tag{7}$$

$$\frac{U}{R} = \frac{U}{R_1} + \frac{U}{R_2} + \frac{U}{R_3} \tag{8}$$

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}, \tag{9}$$

the higher resistance of the series arrangement compared to the parallel arrangement can be demonstrated by assuming the following:

$$R_1 = R_2 = R_3 = R_n \tag{10}$$

and using formulae 4 and 9:

$$R_{ser} = R_1 + R_2 + R_3 = 3R_n, \tag{11}$$

$$\frac{1}{R_{par}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}, \tag{12}$$

$$R_{par} = \frac{1}{3} R_n, \tag{13}$$

$$9R_{par} = R_{ser}. \tag{14}$$

Resistors can also be used for rotor speed control, in which case they are used to reduce the excitation current. When the excitation is weakened, the rotor speed increases while the electromagnetic torque decreases.

This type of start-up has significant drawbacks:

1) it is energy-intensive – the energy lost in the resistors (equal to the work done, $E = \Delta W$) is converted into heat ($\Delta W = Q$); (E – energy, W – work, Q – heat);
2) the resistors themselves have considerable mass;
3) rotation speed and voltage are limited by the commutator (sparks appear at high voltage values), which must be subjected to frequent maintenance (due to heating, brush wear, accumulation of dirt or debris);
4) it is somewhat failure-prone.

2.2. Pulse start-up

Pulse start-up allows the use of not only a DC motor but also a three-phase (synchronous, asynchronous) maintenance-free motor. Frequency control enables smoother starting and eliminates the need for resistors or contactors.

Thyristors

Compared to resistor start-up, pulse start-up offers higher efficiency by eliminating energy / heat losses in the start-up resistor. In this case, the losses, though minor, come from commutation and the voltage drop across the closed thyristor. A further advantage of thyristors is that the voltage is regulated smoothly.

The thyristor consists of power semiconductor elements with three P-N junctions and a control electrode [2, 3, 4]. The thyristor's operating principle is based on the thyristor itself behaving as a current switch with a very short on/off time (several ms), including the current to the load (e.g. a motor). Regulation of the average voltage value is effected through pulse-width modulation. To comply with the minimum switch-on and switch-off times, a variable frequency is used. The traction converter is made up of:

- a main thyristor,
- cut-off thyristor,
- diodes,
- commutation circuit,

whereas cooling is provided by air, oil or another liquid. During operation, the main thyristor regularly changes its operating mode: forward blocking mode, forward conduction mode, reverse blocking mode. When a short pulse reaches the control electrode, the thyristor enters a pass-through mode and the entire source voltage flows through the load (motor). If the triggering thyristor closes, the polarity is temporarily reversed on the main thyristor, which puts it into forward conduction mode; once polarity is restored and no current flows through the motor, the thyristor goes into reverse blocking mode. The change in control frequency manifests itself acoustically (through tones audible to humans), for example, when starting the vehicle. For Škoda's locomotives, the engines start at a modulation frequency of 33.3 Hz; a speed increase occurs at 100 Hz and 300 Hz, and running without changing the speed at 100 Hz. The excitation of the traction motor electromagnetic field is smooth and is carried out between 60 km/h and the maximum speed, i.e. 120 km/h. Thyristor types are as follows:

- reverse blocking triode thyristors (ordinary thyristors),
- reverse conducting thyristors (RCT) (with reverse blocking to reduce the voltage drop in forward blocking mode),
- gate turn-off thyristors (GTO) (which reduce the turn-on and turn-off times and energy losses),
- thyristors with IGBT transistors (with even shorter turn-on and turn-off times than GTO thyristors).

The GTO thyristor consists of four P-type and N-type semiconductor layers, and the design of the device differs little from an ordinary thyristor [5]. It is also acceptable to treat the semiconductor layers as a coupled pair of transistors (a PNP and an NPN one), just like in the case of ordinary thyristors. The pins in the GTO are called the anode, cathode, and gate. If a pulse of current flows through the gate, the thyristor conducts current. GTO thyristors offer three operating modes:

- reverse blocking mode,
- forward blocking mode,
- forward conduction mode.

When the gate is triggered by a pulse, the thyristor enters „forward conduction mode" and continues to conduct until the forward current value drops below the holding current threshold. Apart from featuring the normal characteristics of a thyristor, the GTO makes also it possible to control its "off" state by negative pulses. In ordinary thyristors, the "switch-off" function activates automatically.

GTO thyristors enable the switch-off, i.e., the transition from the conduction state to the blocking state, by means of a control signal in the form of a current in the gate circuit, with a vector opposite to that of the switch-on, and a much larger value. GTO thyristors have a comparable structure to normal thyristors (with a closed-loop triode) and a similar principle of switching on and conducting the current, but with a much more complex surface division of the layers forming the J3 junction (P-N junction, third from the anode). Thus, the control electrode is spread over the entire cross-section of the thyristor, allowing the thyristor to be switched off by introducing a pulse of iRG current into the gate circuit. This pulse has the opposite direction and is many times larger than the iFG pulse, which turns on the thyristor. Table 1 shows a comparison of an ordinary thyristor and GTO for U = 1.6 kV and I = 350 A.

Table 1

A comparison of an ordinary thyristor and GTO for U = 1.6 kV and I = 350 A

Parameter	Parameter description	Thyristor	GTO
$U_{T\ on}$	voltage drop in on state	1.5 V	3.4 V
t_{on}, $I_{g\ on}$	switch-on time, gate current	8 μs, 200 mA	2 μs, 2 A
t_{off}	switch-off time	150 μs	15 μs

[Authors' own elaboration].

Transistors

An IGBT (insulated gate bipolar transistor) is a bipolar transistor with an insulated gate. It is a semiconductor component used in converters generating up to several hundred kV [6, 7, 8]. It offers easy control of field-effect transistors and the high breakdown voltage and switching speed of bipolar transistors. In other words, it combines the strengths of two types of transistors – a bipolar transistor and a field-effect MOSFET one. See Table 2 for a comparison of bipolar, MOSFET, and IGBT transistors.

Table 2

A comparison of bipolar, MOSFET and IGBT transistors

Characteristics	Bipolar transistor	MOSFET transistor	IGBT transistor
Voltage range	<1 kV	<1 kV	>1 kV
Current range	< 500 A	< 200 A	> 500 A
Input current	h_{FE} range ~ 20–200	U_{GS} voltage ~ 3–10 V	U_{GE} voltage ~ 4–8 V
Input resistance	low	high	high
Output resistance	low	medium	low
Switch-on speed	low [µs]	high [ns]	medium
Price	low	medium	high

where: $\beta = h_{FE}$ – amplification factor, U_{GS} – Gate-Source voltage, U_{GE} – Gate-Emitter voltage [Authors' own elaboration].

IGBT transistors are currently used in inverters as switches and components for switching currents > 1 kA and blocking voltages < 6 kV.

A semiconductor device developed in the 1980s, IGBT has three terminals: emitter, collector, and gate. It can handle more power and has a higher switching speed, making it highly efficient. The IGBT features the combined characteristics of a MOSFET and a PNP bipolar junction transistor (BJT); it is controlled through a gate like a MOSFET, while its actual voltage characteristics are those of a BJT transistor.

The MOSFET transistor controls the base of the bipolar transistor, providing a rapid transition from the blocking to the conducting state and vice versa. For IGBTs, the blocking state occurs when the voltage between the gate and the source is lower than the threshold value $U_{GS(th)}$, a quantity known to anyone familiar with a MOSFET transistor. The accompanying drain-source voltage results in a very small leakage current. Conduction begins if the gate-source voltage exceeds the threshold value $U_{GS(th)}$ of the MOSFET incorporated into the IGBT – the drain current determined by the collector-emitter voltage and the control voltage value U_{GE} starts to flow.

IGBTs can be used for high voltages and are easy to control. The IGBT transistor structure allows the positive features of both transistors to be combined, and when used as a switch, an IGBT can be employed in systems generating voltages of several hundred kV, operating at a switching frequency of around 50 kHz. The value of the blocked voltage is > 6 kV, which allows this type of transistor to operate freely at > 400 V. The described circuit has both advantages and disadvantages, which are described below.

1) advantages:
   - the ease of control of the IGBT transistor is related to the change in potential of the isolated gate, which greatly simplifies IGBT's design;
2) disadvantages:
   - a significant voltage drop across the IGBT in the conducting state (around 2.5 V), though still not as high as in the case of a classic bipolar transistor,
   - limited operating temperature, from –20°C to approximately 150°C (junction temperatures),
   - the occurrence of the so-called „tail current" during transistor switch-off, extending the real switch-off time, which results in the need to dissipate minority charges from the gate area.

Today, inverters featuring IGBT transistors are the cheapest devices for powering DC and AC squirrel-cage electric motors. The advantage of IGBT transistor inverters over thyristor GTOs is related to the fact that GTOs are discrete components, requiring expensive gate drivers, but offering higher powers or higher voltages in return. GTOs also need to short-circuit protection, i.e., additional circuits must be provided. Indeed, as a consequence of the advantages of IGBT transistor circuits over thyristor GTOs, the former are displacing the latter. Table 3 compares GTOs against IGBTs.

Table 3

A comparison of GTOs and IGBTs

Characteristics	GTO	IGBT
Description	thyristor variant	transistor variant
Number of connectors (GTO)/ terminals (IGBT)	3; anode, cathode and gate	3; emitter, collector, gate
Gate current	current pulse required for switch-on	constant voltage supply required
Number of connections	3	1
External current switch-on/switch-off devices	not needed	required
Application	high voltage generation	

[Authors' own elaboration].

3. Beginnings of DC and AC electrified power lines on the ČSD network

In the early 1950s, few of Czechoslovakia's railway lines were electrified. Among them were two lines: Tábor – Bechyně and Certlov (now Rybník) – Lipno nad Vltavou, as well as railway lines within the Prague Junction, electrified at 1.5 kV DC [9]. At that time, many European railway operators considered electrifying their railway lines with alternating current at an industrial frequency of 50 Hz. In the end, the 25 kV system was selected (20 kV was initially considered) based on the positive experiences observed during its use on the Schwarzwald (Black Forest) railway line in Germany. The line had been electrified at 20 kV (and raising the voltage from 20 kV to 25 kV significantly improved the performance). Both systems – DC and AC – have some advantages and disadvantages.

The 25 kV AC system requires only a single conversion at the transformer stations, so this voltage can be supplied to the overhead line, when lowered from, for example, 110 kV. Furthermore, transmitting a current with a high voltage means less loss – it has a lower intensity and therefore generates less resistance in the conductor. It enables the use of an overhead line with a smaller contact or catenary wire diameter (and thus less weight), as well as lighter overhead line poles. In addition, 25 kV requires the construction of feeder substations every 50–60 km whereas for 3 kV this distance is every 20–30 km. These factors make electrification and subsequent maintenance of a 25 kV 50 Hz railway line cheaper and simpler than a 3 kV DC one.

The advantages and disadvantages of the two voltages in supplying electric locomotives are also different. In the simplest of terms, voltage regulation at the terminals of a DC motor supplied directly from the overhead line, e.g., at motor start-up, is effected by attaching an array of resistors, which results in a relatively high current consumption (the electrical energy in the resistors is converted into heat, i.e., it is lost). Locomotives supplied with AC from the catenary enable a more extensive regulation of voltage and current by the transformer (the current is then rectified in a silicon rectifier; this may also be done earlier in a mercury rectifier/ignitron), resulting in lower energy losses compared to a 3 kV supply. Compared to direct current, alternating current has also proved to be more advantageous in powering high-speed trains (enabling high power at the pantograph). However, the production of AC rolling stock in the 1950s or 1960s was much more expensive and complex than DC locomotives. Once pulse control of traction motors became commonplace, the purchase prices of the two vehicles (DC and AC) were not so drastically different.

The weighing up of the strong and weak suites of both voltages resulted in many railway operators, including the ČSD, opting not to abandon 3 kV in favor of 25 kV 50 Hz and implementing both power supply systems on their railway network. The decision to adopt 25 kV 50 Hz as the prospective voltage for the ČSD network was taken in 1959 and the site for the production of alternating current rolling stock was to be the Škoda factory in Pilsen. The factory also became a leading manufacturer of electric locomotives, not only for the domestic market but also for export (Fig. 1–5).

Fig. 1. EP05-23 (3 kV DC, 1,435 mm) at the Warsaw Olszynka Grochowska locomotive depot (7 February 2017) [photo by S. Dębski]

Fig. 2. 182 157 (3 kV DC, 1,435 mm) at the Białystok railway station (26 March 2011) [photo by M. Graff]

The first test section of ČSD's network electrified at 25 kV 50 Hz was the Plzeň – Horažďovice Suburb line. In 1961, it was decided to use the electrified section Plzeň – Koterov – Blovice (part of the above section) to test new AC locomotives manufactured for the USSR and Bulgarian railways. Further lines electrified at 25 kV 50 Hz were Kutná Hora –Havlíčkův Brod – Jihlava and Havlíčkův Brod – Brno. Currently, the SŽ and ŽSR[2] networks have the following voltage change sections (3 kV DC ↔ 25 kV 50 Hz):

- Kadaň-Prunéřov – Klášterec nad Ohří, Chomutov – Cheb line (SŽ),
- Beroun seřaďovací nádraží – Zdice, Prague – Plzeň line (SŽ),
- Benešov u Prahy – Bystřice u Benešova, Prague – České Budějovice line (SŽ),
- Svitavy – Březová nad Svitavou, Česka Třebova – Brno line (SŽ),
- south of Púchov station, Žilina – Bratislava line (ŽSR);

or on the following stations:

- Kutná Hora hl. n., Kolín – Havlíčkův Brod line (SŽ),
- Říkovice (Nedakonice until 2021), Přerov – Breclav line (SŽ).

Fig. 3. CS7-088 (3 kV DC, 1,520 mm) with a long-distance train, Yaroslavsky Station, Moscow (29 June 2006) [photo by M. Graff]

Fig. 4. CS4-132 (25 kV 50 Hz, 1,520 mm) at Kyiv station (1 May 2013) [photo by M. Graff]

At the Kutná Hora hl. n., it is possible to supply the overhead line within the entire station using both systems depending on demand, although this is not currently practiced. The peculiarity of the SŽ and ŽSR railway network is that northern Czechia and Slovakia (Prague, Olomouc, Žilina, Košice) are electrified at 3 kV DC, whereas the south – including České Budějovice, Brno, Břeclav and Bratislava – at 25 kV 50 Hz AC. Thus, the use of dual-system locomotives is widespread. The ČD or ZSSK vehicles can also easily travel into neighboring Poland, which uses the 3 kV DC voltage, as well as into Hungary, where 25 kV 50 Hz AC is used. Travel to Germany and Austria is similarly uncomplicated and is carried out using vehicles supplied by Škoda and, in recent years, a range of rolling stock delivered by Siemens (Taurus, Vectron, ES64F4) and Bombardier (Traxx).

Fig. 5. CS4^{T}-603 (25 kV 50 Hz, 1,520 mm) with a long-distance train to Brest, Minsk (28 June 2006) [photo by M. Graff]

4. Škoda's first locomotives with pulse engine start-up

Below is a description of the gradual implementation of pulse traction motor start-up, which first took place in shunting locomotives.

4.1. E458.0, E458.1 and S458 series (110, 111, 210)

In 1971, Škoda produced the first Type 33E locomotives, designated by ČSD as the E458.0 (110) series, equipped with resistor traction motor start-up and designed for shunting operation on 3 kV DC electrified stations, as well as for local traffic (Fig. 6) [9–13]. Two locomotives (No. 018 and 047) were put to work on lines electrified at 1.5 kV DC (Tábor – Bechyně, Rybník – Lipno), where locomotives of the 113 series, a variant of the 110 series, were already in service. In 1979, Škoda in cooperation with ČKD Elektrotechnika decided to install two thyristor converters instead of starting resistors in the E458.0[3] locomotive as

[2] SŽ and ŽSR are the railway infrastructure managers in Czechia and Slovakia, respectively; they are the equivalents of Poland's PKP PLK.

an experiment (Fig. 7). The new solution made economic sense since the locomotive was used in shunting work, requiring low-speed driving and frequent starting and stopping. Measurements showed that 200 MWh of energy was saved during the year compared to a locomotive utilizing resistance start-up. Additionally, pulse start-up does not require devices such as contactors and all the complex apparatus used in resistance start-up. When the thyristor converters were supplied with a pre-current in the 40–3560 V range, the control frequency varied from 33.3 to 100 to 300 Hz; e.g. the first reduction of the excitation of the traction motor electromagnetic field occurred at a frequency of 300 Hz (full pulse). After the supervised operation of the E458.1 (111) locomotives with pulse start-up, the new vehicle was found to be more economical than the E458.0 (110) series. Comparing the two vehicles in this respect, the following energy savings were achieved:

- when running idle – 17%,
- at the ride to the hump yard – 55–60%,
- average consumption per hour of shunting – 50%.

Fig. 6. 110 026 (ZSSK) at the PKP/ŽSR border station Plaveč, Slovakia (8 February 2009) [photo by M. Graff]

Fig. 7. 111 019 (ČD) at Praha Smichov station (8 March 2008) [photo by M. Graff]

4.2. Description of the electrical and mechanical parts of the 110/111 series locomotive

The 110/111 series are four-axle locomotives with individual traction motor suspensions, which are supported by springs on the bogie frame [9, 10, 14]. Motor torque is transmitted to the wheels by a gearbox with a one-sided straight-toothed gear. The locomotive bogies are two-axle, fully welded, and feature backlash-free wheelset guiding. The tractive forces are transmitted through the pivot and also through a system of angled hangers. The vehicle's suspension is two-stage: the first stage is cylindrical springs and the second comprises cylindrical springs and hydraulic dampers. The locomotive is equipped with an electro-pneumatic mechanism for neutralizing changes in the load of individual axles on the track during travel. The center section of the locomotive houses the driver's cab, equipped with two control panels (one for each travel direction). On the roof of the locomotive, there is one asymmetrical pantograph adapted for 3 kV DC, as well as an HV cable, and a grounding protection system. The locomotive features resistance start-up, with the starting fechral resistors[4] themselves located on both sides of the cab in the locomotive's depressed engine compartments (for the 110 series). The locomotive has four six-pole, forced air-cooling DC traction motors. The electrical apparatus is grouped in both machinery compartments of the locomotive in such a way that each can be removed as a single piece should the need for disassembly arise. The compartments also house the louvers and filters for engine cooling air intake and starting resistors. The locomotive can also be fitted with an autocoupler in which case it is necessary to remove a total of 8 t of ballast (the maximum tractive force is then reduced from 180 kN to 160 kN). The locomotive is fitted with a DAKO system brake, one compressor (two in the case of the 111 series), and two air tanks with a total capacity of 1,000 liters. The vehicle is fitted with anti-skid devices. The power controller for the 110 series locomotives has 36 driving positions, whereby it is possible to reduce the excitation of the (magnetic field of the) traction motors by up to 50%. Each vehicle has been fitted with an LS IV traffic safety system.

Between 1981 and 1982, 35 pulse start-up locomotives (111 series) were produced for ČSD, and

[3] Originally, this was locomotive E 458.0012. Damaged by fire, it was designated E 457.0001 after refurbishing (112.001-3). The locomotive was in service until 1996 and was scrapped in 2001.

[4] Fechral or FeC(h)rAl – it is an abbreviation of FeC(h)rAl – iron, chromium, and aluminum.

now all are owned by ČD. As for the 110 series, the following number of units is currently in use: ČD+ZSSK – 28+22 units out of the 52 units produced for ČSD. The 110/111 series locomotives are used mainly for shunting work and occasionally for hauling freight or light passenger trains on both the Czech and Slovak railway networks. They also appeared occasionally on the PKP network, hauling passenger trains between Slovakia's Plaveč via Muszyna to Krynica. The 110 series vehicles are stationed at Czech and Slovak locomotive depots in Košice, Ostrava, Prague, Ústí nad Labem, and Žilina, and the 111 series vehicles are stationed only at ČD locomotive depots Bohumín, Hradec Králové, Ostrava, Prague, and Ústí nad Labem.

4.3. Series 113

A variation of the 110 series, the 113 series is suitable for operation on lines electrified at 1.5 kV DC [5, 10, 14]. Six vehicles were built to handle passenger traffic on the Tábor – Bechyně and Rybník – Lipno lines, replacing the 100 series locomotives used previously. The 113 series vehicles were stationed in two locomotive depots, Tábor and Vyšší Brod (3 units each). After the year 2000, ČD decided to electrify the Rybník – Lipno line, part of the České Budějovice – Summerau (border crossing with Austria) line, with a voltage of 25 kV 50 Hz; this took place in April 2004 (the last 1.5 kV DC train traveled on the route in October 2003). Although two locomotives were taken to Prague, where both were converted to 110 series standard and renumbered 110 205 and 110 206, respectively, they were eventually scrapped along with one more 113 series vehicle. The remaining 113 series vehicles were stationed at the Bechyně locomotive depot near Tabor and operated until 2010–2011, running trains with two-axle Btax780 cars, when part of the traction service was handled by the 814 series units, i.e. diesel railcars.

4.4. Series 210

The S 458.0 (210) series is a modification of the E 458.0 (110) locomotive, which retains the mechanical part of its predecessor – E458.0. The electrical part of the locomotive was changed (these were ČSD's first locomotives to be equipped with pulse start-up as a standard) and adapted for operation on 25 kV 50 Hz electrified lines (Fig. 8) [5, 9, 14]. This required the installation of a transformer (with oil free-cooling), which was placed under the driver's cab. Current from the catenary is routed through a transformer, where, as low voltage, it passes from the secondary winding through two counter-parallel thyristor voltage regulators and two diode bridges and then to the motors. The motors are grouped and can operate in three modes:

- normal running – each pair of motors is connected in groups and supplied from a separate converter, the voltage at the traction motor terminals is seamlessly regulated;
- running with full traction motor excitation in the 0–20 km/h speed range, e.g. during shunting at a hump yard,
- slow running with full traction motor excitation in the 0–5 km/h speed range, after pushing the rail cars down the hump yard.

Fig. 8. 210 040 (ZSSK) at Bratislava Predmestie station (22 August 2006) [photo by M. Graff]

This ensures the locomotive has good traction during heavy shunting work, thus maintaining a suitable speed when hauling local trains. The S458.0 (210) series can also be fitted with an autocoupler.

A total of 74 S458.0 series locomotives were produced; the series was renumbered 210 in 1988, and the vehicles were split between Czechia and Slovakia after the dissolution of Czechoslovakia. Today, the following locomotives remain in service: 24 ČD locomotives and 6 ZSSK locomotives. One new feature was equipping the locomotives with batteries (in a separate coupling car), which allowed them to travel a total of 40 km on non-electrified lines, thus making them more universal. Like the 110/111 series, the 210 series is used for shunting work as well as for hauling freight and passenger trains. The 210 series vehicles are stationed in locomotive depots located in České Budějovice, Tabor and Plzeň, as well as in Slovak locomotive depots in Bratislava and Zvolen. One ČD Cargo 210 series locomotive was fitted with a Caterpillar diesel engine and renumbered 218 series. KDS Kladno owns one locomotive (210 037); twenty locomotives the type 51E were delivered in 1994 to the Bulgarian railways, where they are currently used in shunting and designated Series 61 (Fig. 9).

Fig. 9. 61 010 (BDZ) at Sofia Main Railway Station, Bulgaria (6 October 2019) [photo by M. Graff]

5. Traction locomotives built in the 1970s, i.e. vehicles with resistor traction motor start-up, optionally with high-voltage control

The first vehicles built in the 1970s for passenger traffic still had resistor traction motor start-up (350 and 150/151 series), as did the locomotives built in the early 1980s for freight traffic (131 series). Vehicles suitable for operation on 3 kV DC and 25 kV 50 Hz electrified lines were also created at the time.

5.1. Series ES499.0 (350)

At the turn of 1968 and 1969, with the increase in train speeds, the Czechoslovak railways placed an order with Škoda for passenger locomotives designed to run express trains on 3 kV DC and 25 kV 50 Hz AC electrified lines, with a maximum speed of 160 km/h, 4,000 kW of power and a weight of up to 88 t. To this end, new bogies were tested in 1972 on locomotive E 469 3030 (124 601-6), with a view to using them in the new series of vehicles. Two prototypes designated ES 499.0 were developed in 1973 and 1974, after which the first two units were produced in 1974 and 1975, designated ES 499 0001 and ES 499 0002, respectively. The series brought significant innovation to the ČSD railways in the form of an electrodynamic (resistance) brake (Fig. 10).

The locomotive is fitted with 2 biaxial bogies with column-guided wheelsets [5, 9, 14]. Fully sprung traction motors are mounted on the bogie frame. Transmission is via a Škoda-type gearbox. The locomotive body has thermally and acoustically insulated driver's cabs at both ends, each featuring an extra air supply system. The windscreens are fitted with a frost removal system and a water/detergent mixture spraying system. The locomotive has a two-stage suspension consisting of cylindrical springs and hydraulic dampers. Tractive and braking forces are transmitted through a pivot surrounded by a rubber cap. No bogie coupler has been fitted. When running at 3 kV, the current flows through the main voltage fuse and then to the motors; while when running at AC, it initially flows through a voltage-reducing transformer and then to the motors. The locomotives feature a safety device that blocks their control system in the event of an electrical fault. The traction motors are started by resistors controlled by an electro-pneumatic mechanism. The unit power of the engine is 1,000 kW (the total power of the locomotive is 4,000 kW). Two fans were used to cool the resistors, traction motors, and transformer, with air being directed to them through louvers located in the side walls of the locomotive body. The main transformer is located in the middle portion of the locomotive, just under the main frame. The vehicle is equipped with a DAKO-LR air brake with an anti-skid mechanism. The vehicle also features an electrodynamic resistance brake, operating in the 60–160 km/h speed range, regardless of whether the locomotive draws voltage from the overhead line or not. The locomotives have been fitted with a system that provides more automated guidance compared to earlier models. The rail cars can be heated from the locomotive in two ways: directly from the overhead line with 3 kV DC running, and from a transformer at 1.5 / 3 kV 50 Hz with AC running. The locomotive control method and traction characteristics are virtually identical for both power systems. The maximum speed of the vehicle is 160 km/h (a top speed of 182 km/h was achieved during test drives).

Fig. 10. 350 014 (ZSSK) with the IC 532 Rákoczi train on the Budapest – Košice route, as seen at the MÁV/ŽSR border station Hidasnémeti (28 March 2009) [photo by M. Graff]

The 350 series has been running trains on the ČSD network since the beginning of its service on the Štúrovo – Bratislava – Prague route (the two power supply systems – 3 kV DC and 25 kV 50 Hz AC – intersect at Kutná Hora hl. n.), and has also been traveling to Budapest since 1975. As late as the mid-1990s and early 2000s, passenger trains traveling through Czechia would still occasionally be hauled along the entire ČD network by locomotives belonging to foreign railways, e.g. EC Hungaria on the Budapest – Berlin route. In turn, the Budapest – Bratislava – Praha Holešovice route was served by a ZSSK 350 series locomotive, whereas the Praga Hol. – Dresden – Berlin route was served by a DB series 180 locomotive. Currently, EC/IC trains on the Prague – Dresden route are run by ČD Vectron 373 series locomotives. The entire 350 series (18 units remain out of 20 produced) is stationed in Bratislava. Together with the ČD 151 series, the 350 series locomotives achieve the highest average daily mileage of around 1,000 km. Since 1997, along with the increase of travel speeds on ČD transit lines to 160 km/h, the locomotives were upgraded at ŽOS Vrútky, receiving a new MIREL diagnostic system and vibration dampers to improve their running characteristics, as well as a new color scheme, changed from blue and cream to red and cream. In 2005, Pendolino trains to ČD railways were introduced to serve the Prague – Bratislava/Vienna route, and in early 2009, ÖBB railway's Taurus 1216 locomotives to run on the Vienna – Břeclav – Prague route, too. Previously used on the Břeclav – Prague section, the 350 series locomotives of the Slovak railways ZSSK began running IC trains on the Budapest – Miskolc – Košice route via the Hidasnémeti – Čaňa border crossing and continue to do so along with the 363 series (7 pairs of trains). Until December 2014 and the introduction of ČD 380 series locomotives, the 350 series was used to service EC, IC, and Ex passenger trains on the following routes:

- Prague – Olumouc – Ostrava – Žilina – Košice,
- Prague – Brno – Břeclav – Bratislava – Štúrovo – Budapest.

The 350 series locomotives continue to run trains on the following routes:

- Bratislava – Žilina – Poprad – Košice,
- Košice – Hidasnémeti – Miskolc – Füzesabony – Hatvan – Budapest,
- (Prague – Brno)/Bohumín – Breclav – Bratislava – Štúrovo – Budapest.

Despite their age (> 40 years), these vehicles are still in service, and one of the reasons for this is that ZSSK lacks funding to purchase new ones. In 2017, ZSSK leased 10 Vectron locomotives (designated 381.1) to operate the Bratislava – Košice line, with similar locomotives approved in the neighboring countries of Czechia, Germany, Austria, Hungary, and Poland, allowing them to temporarily replace the 350 series. One solution to this problem could be to upgrade the 163 series locomotives to the 361.1 standards, which ZSSK is now doing.

5.2. Series E499.2 (150) and 151

In the 1970s, with the increasing weight of passenger trains, the E 499.0 (140) and E 499.1 (141) series locomotives operated by the ČSD had to be double-headed. To rectify this, Škoda designed the E499.2 (150) series vehicle for operation on 3 kV DC electrified lines, which was a further modification of second-generation ČSD locomotives. E499.2 (150) was designed and put into production in 1978. The main concepts like the body, bogies, driver's station equipment, traction motors, and vehicle control were derived from the ES 499.0 (350) series dual-system vehicle [5, 9, 14, 15].

The E499.2 (150) series locomotive is designed to run long-distance and express trains on main lines and has been used for years on the Prague – Košice route. Locomotives of this series can reach a top speed of 140 km/h. The mechanical differences compared to the ES 499.0 (350) series include a bogie coupler, allowing the locomotive to negotiate curves easier. Unlike the ES 499.0 (350) series, which featured hollow axles, the E 499.2 (150) series locomotives were equipped with solid axles. The body has a slightly altered shape compared to the ES 499.0 (350) series dual-system locomotive, including a different layout of the louvers and air intakes cooling the engines and starting resistors. The locomotive is equipped with a 3,600 kW electrodynamic resistance brake operating in the 45–140 km/h speed range for the 150 series and 25–160 km/h range for the 151 series; at lower speeds, the driver can only use the air brake. A pneumatic axle load equalizer is fitted to both bogies. The diagnostic system detects faults in the electrical system and notifies the driver about them. The locomotives were equipped with an automatic speed regulation system (Czech: „automatická regulace rychlosti", ARR); however, practice showed that due to running on higher resistor stages and insufficient cooling of the resistors themselves, the use of the ARR caused numerous failures and thus was discontinued on the locomotives of this series. Some years later, the system began to be removed from the locomotives. All vehicles in this series are fitted with an anti-skid system, a DAKO brake, and an LS 90 safety system (Fig. 11).

After tests (no prototypes were produced) within the Prague junction, the vehicles of this series were assigned to service the Prague – Žilina – Košice route; they were stationed at the Prague locomotive depot. They were later diverted to run on the main line, hauling fast and express trains. A significant shortcoming that became apparent during their operation was the high ratio of inoperative locomotives (~50% or more) due to failures of:

- FeCrAl start-up resistors,
- motors themselves (compensation windings),
- motor suspension on the bogie frame.

Fig. 11. 151 011 (ČD) at Praha hl.n. station (8 March 2008) [photo by M. Graff]

The first locomotive to be written off was E 499 2017, which hit a freight train at 100 km/h near Spišská Nová Ves in 1981. The second locomotive, 151 018, was stricken off the ČD register on 8 August 2008 following an accident involving an EC 108 train, which took place in Studénka near Ostrava.

The modernization of the series was done in 1992 in cooperation between Škoda Plzeň and ŽOS Vrútky, and the maximal speed was increased to 160 km/h. In December 1992, on the Velim test track, a 151 series locomotive reached a speed of 177 km/h. Less than two years later, a total of thirteen 150 series vehicles were upgraded and converted to 151 series, receiving additional hydraulic dampers to improve their running characteristics, an electronic speedometer, a new anti-skid system, and a traffic safety system, as well as a new compressor (one unit instead of two)[5], and windscreen wipers. A positive feature of both series is their high power output, allowing them to run heavy trains without problems.

The 150/151 series, together with the 350 series, currently have the highest average daily mileage on ČD routes, at more than 1,000 km. All 150 and 151 series locomotives are stationed at a locomotive depot in Prague: originally, it was the Praha Střed locomotive depot (now LD Praha Masarykovo nádraží) and later Praha Vršovice. In 1998, all 151 series locomotives were permitted to enter the Slovak railway network. The 151 series is intended to run qualified trains (EC, IC, SC) or fast trains on the ČD network, including such trains as *Manažer* on the Praha hl. n. – Bohumín route (withdrawn after the introduction of Pendolino to ČD), EC *Silesia* on the Praha hl.n. – Bohumin (– Chałupki – Warszawa Wsch.)[6], IC *Ostravan* on the Praha hl. n. – Žilina[7] route, as well as Silesia on the Praha hl.n. – Bohumín route (– Warszawa Wschodnia/Kraków Główny). In contrast, the 150 series locomotives are used to service fast trains between Prague and the stations of Hradec Králové, Jaroměř, and Týniště nad Orlicí, as well as long-distance EN Slovakia trains traveling between Praha hl. n. and Humenné, and the SuperCity Košičan train on the Praha hl. n. – Košice route. Of particular note is the Dukla train, which once connected Prague with Moscow. It was usually led by an E 499 2 locomotive and would haul as many as 20 rail cars in its heyday (gross weight 1,050 t), running between Prague via Čierna nad Tisou to Chop, then part of Soviet Ukraine. Crossing some hills (Horní Lideč, Štrba) required the assistance of a pushing locomotive. The train's speed was limited to 110 km/h due to the Matrosov system brake fitted to SZD railway cars.

5.3. Series S 499.1 (242) electric locomotives of the ČSD (ČD, ŽSR) railways and 43 and 44/45 series locomotives of the BDZ railways

The 1970s electrification of the ČSD network at 25 kV 50 Hz brought a demand for rolling stock suitable for operation at this voltage [5, 9, 14]. For economic reasons, it was decided to adapt the body of the E 469.3 (123) series locomotives to 3 kV DC, with modifications due to the different types of voltage (re-

[5] In two locos the 151 class, monobloc wheels have been fitted.

[6] Previously, most of the trains on the route Warsaw – Ostrava – further Prague, Vienna or Budapest ran through the Zebrzydowice – Petrovice u Karviné border crossing, with a change of locomotive at the Petrovice u Karviné station. Nowdays, all trains go on the changed route, through the Chałupki - Bohumín crossing, and a change of locomotive is made on the Bohumín station, due to more passenger stations for the last route (e.g. Racibórz, Gliwice, Zabrze, etc.). For the route through Zebrzydowice, on the section from Katowice to the border with the Czech Republic, there were practically no stops at passenger stations. In the next timetable, only IC/EC Polonia train is scheduled to run the border crossing Zebrzydowice – Petrovice u Karviné.

[7] Earlier also the IC Jan Perner train, Praha hl.n. – Bohumín.

quiring a completely different electrical equipment); this included adding larger louvers on the vehicle's side walls, a new control panel, and an electrodynamic brake. The locomotives were delivered in three batches – 30 units in 1975, 26 in 1979, and 30 in 1981, for a total of 86 vehicles]. After the separation of ČSD into ČD and ŽSR, the entire series was taken over by ČD and is stationed at the Brno and Plzeň locomotive depots. Although the locomotives were intended to run passenger and freight trains, their low maximum speed of 120 km/h meant that their use was gradually limited to running local trains and possibly some express trains, as the ČSD acquired locomotives of newer series.

The ČSD (ČD, ŽSR) railways S 499.1 (242) series electric locomotive is a 4-axle vehicle designed for operation on lines electrified at 25 kV 50 Hz. It is characterized by a relatively simple design and high reliability, as well as a lack of electronics. The tractive and longitudinal forces are transmitted from the bogies to the main frame by means of transverse traction rods. The vehicle has a two-stage suspension, the first stage being steel springs and the second leaf springs. The wheelsets are column-guided. However, due to limited maintenance, mechanical problems eventually emerged. The transfer of longitudinal forces from the body to the bogies by means of transverse traction rods manifested itself in the vibration of the bogies or even in the breaking of the rods themselves. The unrefined mechanism did not allow the locomotive's power to be fully exploited (Fig. 12).

Fig. 12. 242 221 (ČD) at Brno hl. n. station (9 March 2008) [photo by M. Graff]

The locomotive body rests on a steel main frame and has driver's cabs at either end. The vehicle's side walls have been fitted with louvers to enable the cooling of the electrical equipment and optionally discharge hot air outside. The engine compartment is cooled by two fans installed inside it. The current is received through two symmetrical pantographs, after which it flows through two automatic disconnectors, pneumatic circuit breakers, and a surge arrester. The transformer is installed symmetrically on the main frame; it has 32 taps and utilizes oil cooling. The transformer comprises an autotransformer, an expansion tank, an oil pump, and a Buchholz relay. Once the transformer voltage is reduced, the current is routed through a silicon rectifier to the DC traction motors (one rectifier supplies one traction motor), which are supplied with ripple current (flowing from the AC rectifier before filtering out the AC component). The six-pole traction motors have Class H insulation, are fully sprung from the bogie frame, and transmit torque to the wheelsets via a universal coupling and one-sided Škoda gear. It is possible to achieve the magnetic field excitation of the motors up to 44% at four stages. Voltage (and locomotive speed) regulation is carried out in the 0–1 kV range at the transformer secondary winding using a pneumatic actuator. The electrical equipment in the machinery compartment is arranged symmetrically, with a passageway running through the compartment's center. The traction motors are cooled by fans while the onboard equipment is powered by 48 V DC, supplied by a battery bank mounted under the locomotive frame. The locomotive is equipped with two 3 DSK 100 two-stage three-cylinder piston compressors, which supply compressed air to the vehicle's electro-pneumatic and pneumatic equipment. The two main air tanks are mounted under the locomotive body behind the snow plow. Compressed air is also pumped into two auxiliary tanks. The locomotive features a DAKO system pneumatic service brake, with braking affected by brake pads mounted on both sides of all locomotive wheels. The emergency brake is the handbrake. The vehicle is equipped with the LS IV traffic safety system. While the 242 series continues to be operated by ČD Group companies, the deliveries of Pantera EMUs carried out since 2011 have resulted in a significant proportion of the 242 series vehicles being gradually phased out.

The 43 series locomotives operated by Bulgaria's BDZ (type 68E), delivered in three batches of 56 units between 1971 and 1974, are similar in design to the S 499.1 series (242) of the ČSD railways [16, 17]. While remaining virtually unchanged mechanically, the 43 series vehicles weigh more – 87 t instead of 84 t, have a higher top speed of 130, compared to the 242's 120 km/h, and a lower power output – 2900 kW compared to 3080 kW in the case of the 242 series (Fig. 13). The only difference in the electrical part is an additional capacitor filter immediately upstream of the transformer. Series 43 vehicles were allocated to the Gorna Oryahovitsa and Podujane locomotive depots. In the 1975–1980 (3 deliveries) and 1982–1983 (2 deliveries) periods, 89+60 locomotives of a modified version (Type 68E1) were produced for BDZ and designated series 44 and 45 (Fig. 14) while retaining and continuing the numbering of series 43. The modifications mainly concern the mechanical section – the transfer of tractive and longitudinal forces from the bogies to the body is done by means of a pivot. The second-stage suspension is also different, with cylindrical springs and hydraulic dampers. Another difference between the 43 and 44/45 series is the changed bogie design due to a modified suspension. A reduction in top speed from 130 km/h to 110 km/h and an increase in the tractive force were achieved by changing the gear ratio from 1:3.348 to 1:3.95 (series 45 vs. series 44). The locomotives were assigned to the Gorna Oryahovitsa and Podujane locomotive depots (series 44), as well as Gorna Oryahovitsa, Podujane, Burgas, and Plovdiv (series 45). Between 1995 and 2003, 43 locomotives of the 43 series were overhauled, with their gear ratio changed to 1:3.95 and designation to 43.5. The gearboxes were sourced from decommissioned series 42 locomotives, also supplied by Škoda. The overhaul was meant to provide the railways with locomotives for running freight trains. Today, the 43, 44, and 45 series are the mainstay of traction service on BDZ's electrified lines. The operator initially commissioned upgrades from the Croatian company Končar (two 44-series vehicles in 2004), but in 2019 decided to opt for Czech and Slovak upgraders and dispatched twenty 44-series locomotives to them. The number of 43/44/45 series locomotives owned by BDZ as of 2022 is as follows:

- 43 series: 31 locomotives in service, 20 decommissioned, and 5 sold to other operators,
- 44 series: 43 vehicles in service, 31 decommissioned, and 15 sold to other operators,
- 45 series: 36 in service, 21 decommissioned, and 3 sold to other operators.

Fig. 13. 510.7+43 526.3 (BDZ) at Plovdiv station, Bulgaria (8 January 2016) [photo by HotMusicFan/Wikimedia Commons]

In 2012, ZOS Zvolen purchased 4 locomotives Series 43.5 from BDZ, which were subsequently modernized and adapted for operation on the ČD and ŽSR networks. Slovakia's Railtrans International and Lokorail each obtained a single locomotive, and Loko Trans from Czechia acquired another two. Private operators purchased some of the withdrawn 242 series locomotives from ČD in 2015, which are expected to return to service after modernization.

Fig. 14. 44 061 (BDZ) with a long-distance train at Sofia Main Railway Station, Bulgaria (6 October 2019) [photo by M. Graff]

5.4. Series E 479.1 (131)

The type E479.1 (131) electric locomotive was designed in 1981 to run heavy freight trains on 3 kV DC electrified lines [5, 9, 14]. Though it is a two-unit vehicle, each unit can be operated separately as a single-cab locomotive. Further, the two locomotive units are connected by a screw coupler (UIC). One new feature was the shape of the locomotive body – the focus was on simple geometric shapes. The locomotive's roof has louvers and filters allowing air to pass through to cool the traction motors and FeCrAl starting resistors. The louvres and filters were larger than those previously used on locomotives operating on the ČSD network because the E479.1 (131) series was to run trains of iron ore and coal through complicated mountainous terrain – on the Košice – Bohumín route leading through the Slovak Tatra Mountains range (Fig. 15 and 16).

The traction motors mounted on the bogie frame are fully sprung and the transmission is via a Škoda-type gearbox. The tractive forces are transmitted through the pivot, and the suspension is two-stage, comprising cylindrical springs and hydraulic dampers. The springs are suspended in such a way that it is not necessary to remove the locomotive body when replacing them. The bogies in each locomotive section are connected by a bogie coupler, enabling the locomotive to negotiate curves easier. The wheelsets are column-guided, with some changes compared to the 350/150 series. An axial load equalization mechanism is also fitted. A special beam is installed between the main frame and the headstock, which absorbs most of the energy if the vehicle collides with an obstacle. If damaged, the beam can be easily replaced.

Fig. 15. 131 005 + 131 006 (ZSSK) at Plaveč station, ŽSR/PKP border station (7 February 2009) [photo by M. Graff]

Fig. 16. The joint between the units of a 131 series locomotive [photo by M. Graff]

The locomotive is equipped with an electronic system that notifies the driver of certain faults in the electrical system, as well as of the power controller's position. Apart from that device, the driver has a radio telephone, as well as an ALSN autostop safety system. The power controller has 42 positions, with 37 to 42 being drive positions with reduced motor excitation. The locomotive is equipped with a handbrake and an air brake. In 2000, two 131s were fitted with a new diagnostic system, MIREL (with an option to install it in all 131 series locomotives); the system indicates faults and enables greater locomotive guidance automation. A total of fifty 131 series vehicles were produced, and all are generally used for running heavy freight trains on the Košice – Ostrava route. Their numbering is different from that used by PKP companies, e.g., ET41 (ET41-001-A, ET41-001-B) because ZSSK assigns a separate number to each of the locomotive's units rather than assigning a single number to the entire vehicle. Thus, the first 131 series locomotive has been given the inventory number 131 001 + 131 002.

Today, all 131 series locomotives are owned by the Slovak Railways, though they do enter the neighboring networks operated by SŽ and PLK, both when running freight trains from Košice to Muszyna and when arriving in Zwardoń from Čadca. They also run passenger trains on the Slovak rail network, but this is by no means common. The entire 131 series is stationed at the Spišská Nová Ves locomotive depot (Košice – Poprad – Žilina line).

In early April 2008, on the CNTK test track in Węglewo near Żmigród, 131 series locomotives (131 025 + 131 026) belonging to ZSSK Cargo underwent technical and operational tests to certify them for traffic on the PLK network. Until that time, the 131 and ET41 series were only allowed to enter the ŽSR – Plaveč (ET41) and PKP – Muszyna (131) border stations. The tests were scheduled to last ten days, and to this end, the 131-series locomotive received pantographs with copper pantograph contact strip inserts (two pantographs, the so-called „inner" ones), in line with PKP's regulations applicable at the time[8]. At the same time, the Węglewo track was also home to another testing process involving the ET41-105 type, run for ZSSK Cargo to issue a similar certificate of approval for the ET41 series to operate on the ŽSR Slovak railway network. Under an agreement between the Slovak and Polish railways, ZSSK Cargo's 131 series two-unit electric locomotives were certified for operation on the PLK network in mid-2008. The first of these was 131 025 + 131 026, which ran trains between Košice and Kraków (via the Plaveč – Muszyna border crossing). Eventually, ZSSK Cargo opted to modify the following locomotives to comply with Polish regulations (the process was finalized in late December 2009): 097/098, 009/010, 067/068, 039/040, 063/064, 019/020, 023/024 and 029/030. The modification process consisted of installing a Polish SHP and CA safety systems and radio communications, as well as replacing the carbon pantograph contact strips with copper

[8] As of today, pantographs with graphite contact strips are required.

ones (for a total of two half-pantographs each, with contact strips of both types). When it comes to adapting Polish ET41 series locomotives for operation on the Slovak ŽSR and SŽ networks, this mostly applies to the vehicles stationed at the Czechowice-Dziedzice locomotive depot. Since January 2012, the 131 series locomotives have been running on the extended Haniska pri Košicach – Świnoujście line (on the Bohumín – Zduńska Wola Karsznice – Poznań – Krzyż – Szczecin route).

6. Mass implementation of impulse traction motor start-up

In the early 1980s, Škoda produced locomotives suitable for operation on lines electrified at both 3 kV DC and 25 kV 50 Hz (dual-system, now designated 363/362 series), based on which it later developed single-system versions for both 3 kV DC (163/162 series) and 25 kV 50 Hz (263 series) lines. For communication with Germany, vehicles suitable for 3 kV DC and 15 kV 16.7 Hz (371/372 and 180 series) were produced, though it was decided that these would retain the older (resistor) traction motor start-up system.

6.1. Series ES499.1 (363)

The ES 499.1 (363) series locomotives are dual-system vehicles designed to operate at 3 kV DC and 25 kV 50 Hz (Fig. 17). Featuring universal characteristics, the vehicle is designed for running passenger and freight trains. Running the latter is enabled by the high power output: 3,060 kW at 25 kV 50 Hz and 3,480 kW at 3 kV DC. The first vehicles were ordered in 1976, and the prototype locomotive was presented four years later. In designing the vehicle, it was assumed that the ES 499.1 series (363) would be the baseline design for locomotives adapted for electric power operation only – at 3 kV (E 499.3 and 163 series) and at 25 kV 50 Hz (S 499.2 and 263 series) – so both the mechanical and electrical parts were unified insofar as possible [5, 9, 14, 18]. The body's style referred to the new simple design as used, for example, on the E 479.1 (131) series vehicles. The electric part of the locomotive was designed through a collaboration between Škoda and ČKD Elektrotechnika: two ES 499 prototypes designated 1001 and 1002 were developed. Batch production started in 1985 and was completed in 1990. The prototypes underwent technical and operational tests in December 1980 on the Horažďovice – Plzeň – Cheb route, as well as in the Jihlava area and on the ŽZO Cerhenice test track. After testing, the locomotives were assigned to the LD Jihlava depot. Initially, the vehicles experienced problems with the electronics and thyristor converters, but the manufacturer rectified these faults.

Fig. 17. 363 062 (ČD) (overhead line voltage – 3 kV DC) at Praha hl.n. Station (8 March 2008) [photo by M. Graff]

The ES 499.1 (363) series locomotive is a four-axle vehicle with a separate drive for each axle. Its fully sprung traction motors are suspended from the bogie frame. The power transmission from the motor to the wheelset is via a Škoda-type gearbox. The bogies are unified and it is possible to swap them seamlessly between the different series (363, 263, 163, etc.). The body is set up on the bogies using a two-stage suspension, with the first one based on cylindrical springs and the second on cylindrical springs and hydraulic dampers. The tractive forces are transmitted through the pivot, and the wheelsets are column-guided. The two bogies are connected by a bogie coupler, allowing the locomotive to negotiate small-radius curves easier. Additionally, the locomotive features a pneumatic mechanism to equalize the pressure of the individual wheels on the track. Both sides of the locomotive body are not symmetrical: on one side are the louvres and filters needed to cool the motors and FeCrAl resistors that make up, they electrodynamic brake. On the other side are 4 circular windows. There is a driver's cab at each end of the locomotive body. The locomotive utilizes new generation traction motors: six-pole, compensated with full excitation, enclosed in each bogie (two per bogie), and forming a single unit. The motor terminals are fed from two frequency-controlled thyristor converters – the frequencies used are 33.3 Hz, 100 Hz, and 300 Hz. Full excitation of a group of motors is provided by a single connected converter, and the braking process is initiated by reversing the polarity of the converters and connecting the motors to ED brake resistors (two motors – one resistor). The voltage at the motor terminals, and thus the speed of the locomotive, is regulated seamlessly by a further thyristor converter when the motors are fully excited, enabling economical energy consumption. The locomotive's auxiliary equipment is powered by auxiliary thyristor converters (3,000/600 V). When running at 25 kV 50 Hz, the voltage from the overhead line is routed through the main transformer and then through two rectifiers (at 3 kV in the overhead line, the current flows directly through the converters to the traction motors, bypassing the transformer). The ED brake operates in the 7–140 km/h (362) or 7–120 km/h (363) range, and only the air brake can be used at lower speeds. An ARR system (a type of speed control) was fitted to make the locomotive more comfortable to drive, keeping the set speed within an error margin of up to 3 km/h. Each locomotive is fitted with a DAKO brake, an LS 90 safety system, as well as two compressors, and two air tanks (900 liters in total).

A total of 180 ES 499.1 (363) and one 362 were produced, with the latter having an increased top speed of 140 km/h compared to the former's 120 km/h (Figure 18). At the turn of 1993 and 1994, 15 locomotives were adapted to travel at 140 km/h and renumbered as series 362 while retaining their previous ČD inventory numbers (ZSSK renumbered them starting from number „1"). The adaptation, which was dictated by the need to have vehicles for high-speed qualified trains, involved raising the maximum speed from 120 km/h to 140 km/h by changing the ratio of the main gearboxes and fitting more hydraulic dampers and stronger glass in the front windows. The process of upgrading the 363 series (conversion to the 362 series) also involved swapping bogies with the 162 series (which was renumbered 163.2).

Fig. 18. 362 011 (ZSSK) with an EC train from Prague at Budapest Keleti station (19 June 2013) [photo by M. Graff]

The new locomotives were stationed at first at České Budějovice, Plzeň, Praha Jih, Zdice and Nymburk. After the dissolution of Czechoslovakia, 121 Series 363 locomotives were taken over by ČD and stationed at DKV Brno, České Budějovice, Ostrava, Plzeň, and Praha, and 42 by ŽSR (now ZSSK), with all stationed at Bratislava. The modernized series 362 locomotives were assigned to DKV Praha PJ Vršovice and Bratislava. Today, the 363 series vehicles are stationed at the following locomotive depots: Ostrava, Plzeň, Ústí nad Labem (ČD), Bratislava and Bratislava východ (ZSSK); the 362 series is stationed at Brno and Plzeň (ČD), as well as Bratislava and Bratislava východ (ZSSK).

The 363 series, together with the 362 series, is currently the most popular locomotive traveling on the former ČSD railways; it is used to service both passenger trains (362, 363) and freight trains (363 only) on main lines running through an intersection of both power systems (3 kV and 25 kV 50 Hz). Among other connections, these locomotives (362/363) run EC-class transit trains from Poland through Czechia and Slovakia to Vienna or Budapest, including on the Bohumín – Břeclav (Sobieski, Polonia, Chopin) and Plaveč – Hidasnémeti routes (Cracovia[9]). Due to its higher top speed compared to the 363 series (140 km/h vs. 120 km/h), the 362 series is mainly used for passenger traffic, running EC/IC trains, express trains, and passenger trains on the ČD network, particularly ones headed North to South or vice-versa. On the ŽSR network, the use of the 363/362 series is limited to the Bratislava – Žilina line on which the two power supply systems (3 kV DC, 25 kV 50 Hz) intersect – the only line on the Slovak railway network where this is the case. Many 363 series locomotives have been converted to the 362 series, enabling more versatile use. Out of the more than 180 vehicles produced (now designated the 363 series), around 60 are still in operation, and the ČD and ZSSK groups operate around 100 of the 362 series locomotives.

In mid-December 2008, the Hungarian rail transport authority issued a certificate for the operator ZSCS (Železničná spoločnosť Cargo Slovensko), now ZSSK Cargo, allowing the 363 series to operate on the Hungarian MÁV railway network. Locomotive tests on the MÁV network were performed on the Hegyeshalom – Öttevény and Hegyeshalom – Lébény – Mosonszentmiklós sections. The certification procedure for the 363 series included the installation of the Mirel 1 safety system, version 03, as well as a deadman's foot switch, and a radio communication system. As of today, 3 vehicles of the 363 series (No. 102, 103, and 104), assigned to the VP Bratislava východ locomotive depot, have been adapted in this manner. As of May 2009, as agreed between ZSCS

[9] Krakow – Košice – Budapest, the train is suspended now.

and MÁV, these locomotives have been running freight trains on the Košice – Miskolc route via the Čana – Hidasnémeti crossing without changing locomotives at the border. Two pairs of EC trains servicing the Budapest – Košice route are also planned to travel on the same section with no locomotive change. Indeed, the 363 series also ran trains to the Hungarian capital whenever the 350 series locomotives, currently servicing EC trains on the Bratislava – Budapest route, were unavailable. Until the certification of the 363/362 series, the only Slovak electric locomotives that entered the Hungarian railway network were 240 series vehicles (the 363 series would only travel to the MÁV border stations Komárom and Rajka). Four ZSSK railways locomotives of the 362 series, adapted for operation on the MÁV network, now run IC, EC, and EN passenger trains on the Bratislava hl. st. – Komaróm – Budapest Keleti/Nyugati route. Due to the high axle load (22 t), vehicles of both series are only allowed to enter PKP PLK border stations.

With the purchase of the InterPanter EMUs by ČD, the demand for 363 series locomotives has decreased, but the position of the 363 series in domestic freight traffic appears to be unthreatened, while international freight traffic utilizes the modernized 363.5 series (Fig. 19). More specifically, in mid-2011 ČD Cargo and Škoda Transportation entered into an agreement for the conversion of 30 single-system (3 kV DC) 163 series locomotives to the dual-system 363.5 series (3 kV DC; 25 kV 50 Hz), to be delivered between 2011 and 2014. The conversion was carried out at the Pars nova Šumperk plant, a subsidiary of the Škoda Transportation Group. According to the agreement, the modified locomotives are certified for operation on Czech, Slovak, and Hungarian railway networks. The scope of the upgrade included [12, 13]:

- equalizing the power on both power systems to 3,700 kW (originally, the 363 series operated at different power at 3 kV and 25 kV);
- traction motor modernization (power upgrade to 925 kW);
- replacement of inverters (traction and auxiliary) with IGBT static converters (supplied by Škoda);
- installation of a new Siemens EFAT 6745 transformer;
- enabling recuperative braking on both power systems (AC and DC);
- installing multiple-unit train control;
- installing new hydraulic bogie dampers;
- ballasting the locomotives to a total weight of 88 t to achieve adequate traction and pulling power;
- installing a new microprocessor-based vehicle control system, including cruise control (AVV – automatické vedení vlaku) and MSV Elektronika NVL – a module of the MIREL multiple-unit train control and traffic safety system;
- replacing headlights with LEDs.

Fig. 19. 363 511 (ČD) with a freight train (overhead line voltage – 3 kV DC) near Ústí nad Labem station, Czechia (17 June 2014) [photo by K. Steiner]

Between 2011 and 2013, a total of 30 locomotives were upgraded to the 363.5 standard. The series runs heavy trains not only on the ČD network, but also in neighboring countries – to the MÁV/HŽ border station Gyékényes, as well as Ostrava-Bartovice and Petrovice u Karviné stations (iron ore transport) – and container trains from the Haniska pri Košicach terminal (a station equipped with normal and wider gauge rail network, the latter running from Ukraine), and the CFR/MÁV border station Curtici in Romania.

6.2. Series S 499.2 (263)

The S 499.2 (263) series electric locomotive is designed to service freight and passenger trains on 25 kV 50 Hz AC electrified equipment (Fig. 20). Some solutions in its electrical section were taken from older locomotives produced by Škoda – the 363 series – with the new 263 series locomotives meant to complement the existing fleet. The mechanical part was slightly modified compared to the ES 499.1 (363) series, though no modifications were made to the traction motors.

In the S 499.2 series vehicle (263), each of the four traction motors is fed from the secondary transformer winding [5, 9, 14]. With a seamless frequency control of the traction motors, the locomotive runs smoothly in the 0–60 km/h speed range when the motors are fully excited, and in the 60–120 km/h range, its speed is controlled by smaller degrees of excitation decrease. The low-voltage start-up of the locomotive is done by thyristor converters, with vehicle braking (motor/brake ED system) also performed using a pulse system. Two asymmetrical pantographs are fitted on the locomotive's roof; a high-voltage cable runs from the pantographs and passes through a system that protects the electrical section against atmospheric surges and provides earthing, with the voltage then directed to a transformer equipped with 8 independent windings to power:

- traction engines,
- locomotive's auxiliary equipment,

- traction motor excitation,
- oil pump to cool the transformer and converters,
- rail car heating,
- locomotive's auxiliary devices.

Fig. 20. 263 008 (ZSSK) with a push-pull train at Bratislava hl. st. station (22 June 2019) [photo by M. Graff]

The start-up converter consists of 4 diodes and 4 thyristors with oil cooling. A voltage of 440 V is used to supply the auxiliaries, which can be reduced to 220 V, 260 V, and 300 V as required. During electrodynamic braking, the motors operate at full excitation, and the ED brake is activated by adjusting motor excitation. Braking at speeds below 40 km/h activates the electrodynamic brake automatically, and at speeds of 10 km/h and below, only the air brake can be used. The locomotive's power and top speed are identical to the ES 499.1 (363) series, at 3,060 kW and 120 km/h, respectively.

Two prototypes of the S 499.2 series (263) were produced in 1984 and tested on the Velim test track, covering 100,000 km in the process. Batch production was completed in 1988, and the series (a total of 12 units, including two prototype vehicles S 499.2001 and S 499.2002) was assigned to the Jihlava locomotive depot (now stationed at the Brno locomotive depot) and to the Bratislava locomotive depot (No. 003–012), remaining at the latter to this day. The series has received praise from ČSD staff as being highly reliable and easy to operate. The 263 series runs trains between Brno and Bratislava. The vehicles have an older traffic safety system, the LS III, and no upgrades, e.g. in terms of speed, are currently planned. Following the purchase of the 951 series push-pull trains by ZSSK in 2009, the 263 series was adapted to run similar trains together with the 381 series purchased from Škoda in 2011 (two vehicles).

6.3. Series E 499.3 (163) and E 630

The E 499.3 (163) series locomotive was developed to address the need to replace the 140/141 series while incorporating the technical solutions used in the ES 499.1 (363) series. The E 499.3 (163) series locomotives are single-system (3 kV DC) vehicles whose operation on the ČSD network began in 1984 (deliveries were completed by 1992). They do not differ mechanically from the new-generation locomotives produced earlier, with the only difference being the lower weight of the vehicle due to the absence of a transformer [5, 9, 14]. The other parameters, like top speed and power, are identical. A total of 120 E 499.3-series locomotives (163) and half as many 162 series were produced, most of which (88 and 29 respectively) were allocated to ČD after the dissolution of Czechoslovakia. The series differ only in top speed (120 and 140 km/h), while their power and service weight are the same. The ED brake and thyristor converters for the 163/162 series are similar to those used on the 363/362 series locomotives. Between 1993 and 1994, bogies from the 363 series were installed in some of the 162 series vehicles to determine whether the speed of the dual-system locomotives could be increased in this way. The outcome was positive, and the modified vehicles, a total of 21 (ČD) + 14 (ZSSK) 162 series locomotives, were redesignated 163.2 in 1994 (Fig. 21).

Fig. 21. 163 048 (ČD) with the Vltava train servicing the Moscow – Prague route, as seen at Warszawa Wschodnia station (1 April 2012) [photo by M. Graff]

The 1989 economic crisis and political transition, as well as the dissolution of Czechoslovakia into two states 3 years later, brought financial difficulties for the Czech and Slovak railways. Neither ČD nor ŽSR would accept deliveries of new 163 series locomotives manufactured by Škoda, forcing the latter to seek new customers. Ferrovia Nord Milano Esercizio SA, an Italian operator, declared its interest in the vehicles in 1994 and purchased nine 163 series locomotives. In 1994, the financial situation of both the Slovak and Czech railways was stabilized, and after negotiations, an agreement was reached, with both operators taking delivery of 10 and 40 finished vehicles, respectively. The 163 series locomotives were first assigned to LD Česká Třebová, Olomouc, and Košice. Thus, the vehicles were adapted to meet the requirements of the new customer, FNM, which included replacing pantographs, lowering the body with brake resistors on the roof, as well as adaptation to left-hand traffic, and more (Fig. 22). The locomotives were designated E 630, numbered 01–09 and ran both passenger trains (including push-pull ones) and freight trains. In recent years, FNM has renewed its own rolling stock mainly through the purchase of double-decker electric multiple units. The E 630 series ran between Chiasso and Desio, although it eventually started to be increasingly withdrawn from service. This was exploited by RegioJet, an operator registered in March 2009, which had been trying to gain a share of the Czech rail passenger market in the previous months. Following spring and summer demonstration runs using two leased Siemens diesel MUs Desiro in various regions of Czechia, RegioJet announced its intention to launch long-distance passenger services on the Prague – Ostrava route and thus compete directly with ČD. To this end, the company purchased all nine E 630-series locomotives from FNM in May 2010 and issued a tender for the supply of 50 (Fig. 23) passenger rail cars for long-distance traffic (it ultimately acquired second-hand rolling stock from ÖBB). The first three of FNM's E 630 series locomotives were transported from Italy to the Czech border station of Břeclav in early July 2010 and were subsequently taken to Střelice station. The locomotives were upgraded, which included an increase in top speed to 140 km/h, and were designated as 162 series.

Fig. 22. E 630–05 (FNM) with a local train at Milano Cadorna station, Italy (16 April 2001) [photo by S. Paolini]

Currently, 162 series vehicles are stationed in locomotive depots (ČD and ZSSK) located in Česká Třebová, Dečín, Prague, and Ústí nad Labem (ČD), and Žilina (ZSSK), while 163/163.2 series vehicles operate from Bohumín, Česká Třebová, Dečín, Olomouc, Ostrava, Prague, Ústí nad Labem (ČD), as well as Košice, and Žilina (ZSSK). ČD railway's 163 series locomotives run both passenger trains (mostly on secondary routes where the speed of 120 km/h is sufficient) and freight trains; they have also replaced the previously used six-axle 181 series locomotives and their variants on Czech railway lines, which are abundant with curves. The 163 series locomotives belonging to ZSSK only run passenger trains on the ŽSR network since the ZSSK has the 131 series for operating heavy freight trains. This is because the latter trains require adequate power due to the more complicated profile of railway lines in Slovakia compared to Czechia, which results from Slovakia's mountainous landscape. In the last 10 years, with ČD acquiring 440/650 (RegioPanter), 660 (InterPanter), and 471 (CityElefant) series EMUs, the demand for 163 series locomotives has decreased. ZSSK's 162/163 series locomotives are currently permitted to operate at the PLK Zwardoń border station. The identified ZSSK 163 series locomotive runs passenger trains on the ŽSR – UZ border route between Čierna nad Tisou and Chop, hauling 2–3 rail cars: one for daytime running (ZSSK) and 1–2 UZ sleeping cars servicing the Kyiv – Bratislava – Prague/Vienna route.

Fig. 23. 162 118 (RegioJet) with a Prague – Ostrava train at Hranice na Moravě station, Czechia (19 September 2013) [photo by M. Graff]

6.3.1. Series 163 on the PLK network

In the second half of 2007, four 163 series locomotives belonging to ČD railways started running trains of the PKP IC company on the PLK network (this number was soon increased to 5 locomotives). Initially, they serviced the (Bohumín –) Zebrzydowice – Kraków – Krynica/Rzeszów route, and then also ran the EC Wawel train on the Kraków – Legnica section, as well as the Skalnica train on the Kraków – Zwardoń route. Further, they serviced local connections in the Czechowice-Dziedzice – Kłodzko – Międzylesie – Lichkov area, and long-distance connections on the Warsaw – Łódź or Warsaw – CMK – Katowice –Bohumín routes (the Vltava train servicing the Moscow – Prague route) [12, 13]. The vehicles in question were: 163 044 – *Marysia*, 163 045 – *Wanda*, 163 046 – *Kasia*, 163 047 – *Basia*, and 163 048 – *Jadwiga*. In early November 2012, the Przewozy Regionalne operator leased ten 163 series electric locomotives plus one reserve locomotive from ČD to operate its trains on the PLK network. These vehicles were: 163 021 – *Małgosia*, 163 022 – *Ela*, 163 026 – *Gabrysia*, 163 029 – *Beata*, 163 030 – *Agata*, 163 034 – *Helena*, 163 035 – *Zosia*, 163 040 – *Edyta*, 163 041 – *Kamila* and 163 042 – *Oliwia*, from the Česka Třebova locomotive depot. In Poland, maintaining the vehicles was the responsibility of the Toruń rolling stock maintenance plant, while major repairs were carried out at the parent locomotive depot in Czechia, which the leased locomotives would go to every 40 days. The 163 series replaced the ET22 series locomotives previously leased by PR from PKP Cargo. The lease of ČD's 163 series locomotives by PR ended in late 2015. (Fig. 24).

Fig. 24. 163 030 (leased by PR from ČD) with a local train at Poznań Garbary station (29 March 2014) [photo by M. Graff]

6.4. Series 361

In November 2011, Slovakia's ŽOS Vrútky company presented a prototype vehicle designated 361 001 (a modified locomotive No. 163 053 from the Košice locomotive depot; Fig. 25), featuring increased power from 3,480 to 3,600 kW (at 3 kV DC) and from 3,060 to 3,200 kW (at 25 kV 50 Hz), as well as a top speed increased from 120 km/h to 140 km/h (by changing the main gear ratio and installing additional vibration dampers) [18]. Virtually the entire electrical section (main and auxiliary converters, transformer, control system, and power consumption meter) has been replaced, as were the pantographs. Air conditioning has been installed in the driver's cab. Two more vehicles were qualified for modification, including locomotive No. 362 006, which had been damaged in a fire. A total of five locomotives, designated 361: 001–005, were rebuilt between July 2011 and November 2012. Technical and operational tests of the 361.0 series were carried out in mid-2012 using both power systems, and 80 ZSSK drivers were trained at the same time. After five locomotives had been rebuilt, it was decided to modify the technical documentation and develop a vehicle with an increased top speed of up to 160 km/h, designated the 361.1 series. In early January 2013, the first modified locomotive, No. 361 101 (ex 163 102), was tested on the Vrútky – Čadca section (at 3 kV DC). A total of 23 vehicles were rebuilt, all of which received new inventory numbers – 361: 101–110, 120–130 – between September 2013 and early 2017. The purpose of both locomotive sub-series is to run qualified trains between Košice and Bratislava (the series has been certified to enter the ČD network since March 2016).

Fig. 25. 361 004 (ZSSK) with an IC train servicing the Košice – Bratislava at Poprad-Tatry station, Slovakia (18 September 2013) [photo by M. Graff]

6.5. Series ČSD ES 499.2 / ČD 372, BR 230 / DB 180 and ČD 371

Following the electrification of the Berlin – Dresden – Bad Schandau – Děčín – Prague main line in 1987 (power supply: DR – 15 kV 16.7 Hz, ČSD – 3 kV DC), the ministers of transport of East Germany and Czechoslovakia signed an agreement on the joint operation (by ČSD and DR) of the above section and the purchase for the DR railway of Škoda's new type 80E/76E locomotives (Figs. 26–28). The contract stipulated that some of the equipment for the locomotives would be manufactured by East German companies [5, 9, 11, 19]. The problem that arose early on was the maximum permissible weight of the locomotive, which was 84 t and exceeded the maximum load allowed on the DR network. For this reason, choosing a transformer became problematic – the equipment used on the ES 499.0 (350), and ES 499.1 (363) series locomotives proved too heavy (vehicle weight 87–88 t). Moreover, a transformer capable of operating at 15 kV 16.7 Hz has a higher mass compared to one adapted to 25 kV 50 Hz. The need to limit the maximum load to 21 t per track meant that pulse start-up, with which Škoda had already had several years' experience, was not used on the locomotive. Instead, the more energy-intensive resistance start-up was left in place (perhaps this was also due to the small number of locomotives produced). The mechanical part of the new Type 80E locomotives was the same as that of ČSD's locomotives: ES 499.1 (363), S 499.2 (263) and E 499.3 (163). Nonetheless, the resistance start-up used by this series differed from that previously used on the Czechoslovak railway network. Thus, a solution used by DR railways was adopted: when operating at 15 kV 16.7 Hz, the locomotive's traction motors are supplied directly from the secondary transformer winding (2×1.5 kV), after passing through a rectifier as ripple current (much like in the 242 series). Transformer operation is controlled by two diode bridges. Like the transformer, the diodes are oil-cooled. During DC operation, the traction motors are powered directly from the overhead line. The transformers and some of the AC equipment for all locomotives (delivered to ČSD and DR) were manufactured in East Germany by LEW Hennigsdorf. The locomotive has a 2,200 kW ED (resistance) brake, which operates regardless of whether the locomotive draws power from the overhead line. A SIFA safety system, MESA radio communication system, and a vehicle control system were also installed; in the case of the latter, this was DAKO for ČSD and Knorr for DR. The following auxiliary equipment was also installed: batteries: ČSD – 160 Ah (alkaline), DR – 150 Ah (lead), as well as cables: for train lighting, opening and closing the carriage doors, and others. The locomotive was equipped with one compressor with a capacity of 2.33 m^3/min. The total power of the locomotive is 3,060 kW (at both voltages) and the maximum speed is 120 km/h. The locomotive's power controller has 59 positions: 27 degrees of resistance adjustment, with a further 17 being parallel motor connections and the last five being degrees of motor excitation reduction. Fans powered by the voltage drop across the resistors are used to cool the FeCrAl resistors. Each locomotive is fitted with a traffic safety system: LS 90 (ČD) or PZ 80 (DB).

Fig. 26. 371 015 (ČD) with EC 173 Vindobona, servicing the Berlin – Vienna route, departs the Dresden Hbf. station. (1 September 2000) [photo by M. Graff]

Fig. 27. 180 015 (DB) with a freight train (overhead line voltage – 3 kV DC) near Ústí nad Labem station, Czechia (17 June 2014) [photo by K. Steiner]

Fig. 28. 180 004 (DB) with EC Varsovia at Rzepin station (January 1998) [photo by A. Lubka]

Two types of 80E prototype units, series 372 001 and 230 001 (one each for ČSD and DR) were produced in 1988 and subjected to technical and operational tests. In three years, 19 units of the slightly modified 76E series were produced for the DR railways and 14 units for ČSD. As of today, following changes in rolling stock designations in both countries, ČD's locomotives are designated 372 series and DB's 180 series. The most significant changes to these locomotives affected those operating on the ČD network: 6 were adapted to travel at 160 km/h and redesignated as 371 series. While calls were made for a similar modernization of the 180 series, this did not happen due to high costs; the Škoda plant only refurbished a single locomotive. In retrospect, such a modernization seems pointless, as few sections on the Prague – Děčín route enable travel at such speeds. The 372 series locomotives are currently stationed at the Ústí nad Labem locomotive depot (ČD Cargo), and the 371 series at the Praha Vršovice locomotive depot (ČD). Both series run standard and qualified passenger trains and freight trains (ČD Cargo's 372 series services the latter only) from Prague via Děčín and Bad Schandau to Dresden and sometimes Leipzig. The two power systems (3 kV DC; 15 kV 16.7 Hz) intersect on the Děčín – Schöna section. Until the mid-1990s, locomotives of the 180 series traveled from Dresden or Berlin to Prague itself, but after the modernization of the Berlin – Dresden main line and the increase in speed to 160 km/h in the late 1990s, the 180 series proved too slow and the vehicles were shifted to servicing freight trains. Initially stationed in Dresden, the series was gradually relocated to Berlin (this relocation was completed in 2000). With the relocation of the 180 series, the servicing of long-distance passenger traffic between Dresden and the German capital was entirely taken over by the Adtranz[10] 101 series of the DB railways. Further, the year 2003 saw DB donate a single 180 series locomotive to ČD as compensation for locomotive 372 006 damaged in a July 2001 accident at Dresden Hbf. station (ČD received locomotive 181 001, the sole example of this series in DB's inventory, with a maximum speed of 160 km/h). The Czech Railways designated the locomotive as 371 201. The 371 series locomotives serviced trains on the Praha Holešovice – Dresden Hbf./Berlin section, including EC Hungaria on the (Budapest Kel. –) Praha Holešovice – Berlin Zoo route, Kopernikus on the Prague – Berlin (– Amsterdam) route and EC Vindobona on the (Vienna –) Prague – Berlin route. The 180 series locomotives also traveled to Poland (between 1993 and 2005), where they would take over EC trains in Rzepin and run them to Berlin. Following the modernization of the Berlin – Frankfurt (O) line and the increase in speed to 160 km/h, the 180 series was replaced by ČD's 371 series (between 2004 and 2007). Whenever the 371 series locomotives were unavailable, they would be replaced by DB's 234 series diesel locomotives. Subsequently, train operations on the Berlin – Rzepin route were taken over by Traxx E186[11] series locomotives leased by DB from Angel Trains, and in mid-2010, the operation of passenger trains (including EC) linking Berlin and Warsaw along the entire route was taken over by PKP IC's EU44 series Husarz locomotives. The 180 series then became the property of DB Schenker Rail Deutschland and all locomotives were stationed at the Leipzig locomotive depot. At the time, 14 vehicles (002, 006–012, 015–020) were operational, and the remainder were withdrawn. Notably, the continued servicing of Czech-German freight trains, including express container trains arriving from the west to Kutná Hora hl. n. station, by 372 series (ČD Cargo) and 180 series (DB Schenker) locomotives seemed to be in no immediate jeopardy merely a few years back. However, most freight traffic between Germany and Czechia has now been taken over by the 189 series, which travels to Děčín. Moreover, the future of the 180 series came into question following the introduction of the 380 series on the ČD railway, as well as the takeover of part of the passenger traffic on the ČD network by Taurus (1216 series) locomotives belonging to ÖBB and ČD railways (servicing the Vienna – Prague – Berlin route). For DB Schenker, the operation of the 180 series gradually became increasingly problematic due to the small number of these locomotives and their unusual technical solutions. Thus, the operator deposited five 180 series vehicles at Rostock Seehafen Nordost station (180: 002, 007, 009, 010, and 019), with two others (180: 004 and 005) already awaiting repair or decommissioning at the Dresden-Friedrichstadt locomotive depot. Such was also the case with locomotive 180 003. In early January 2013, DB Schenker's condition indicated that the company had a work schedule requiring 7–10 locomotives of this series to service the Dresden – Děčin route, which also reached Engelsdorf station in Germany (a large freight station near Leipzig), and possibly Lovosice, Všetaty and Nymburk stations in Czechia. Occasionally, the 180 series would also run EC trains if none of ČD's 371 series locomotives was available. Though Škoda Transportation expressed its intent to purchase the locomotives stored at Rostock station in late 2012, no such transaction took place. Arriva had also expressed an interest in purchasing 180 series locomotives, but after its takeover by DB, the future of the five locomotives in question seemed unknown.

Additionally, between 2004 and 2006, a partnership between ČD and DB Schenker was considered to take over both series 180 and 372, assuming the vehicles would be modernized beforehand. To that end, two 180 series locomotives, 017 and 018, underwent a conversion process at the Přerov repair plant (DPOV Přerov) at the turn of 2005 and 2006. In the end, the Czech central authorities abandoned the plans to privatize ČD Cargo or sell it to foreign entities. Facing a protracted process to certify ČD's 380 series locomotives for access to the DB Netz network (this series was to replace the 371 and partially 372 series), ČD Cargo signed a contract with Siemens in April 2016 to supply five Vectron triple-system locomotives (ČD designation 383) to replace the 371 and 372 series locomotives running trains between the Czechia and Germany. The Vectrons took over traction service from the 371 series in December 2017. After 2010, when the four-system 189 series operated by DB Schenker (now DB Cargo) was permitted on

[10] Bombardier in 2000–2020, now Alstom.

[11] Similar vehicles were leased by PKP Cargo (the EU43 class) until the beginning of 2011, and now they are purchased or leased by private operators (e.g. Lotos Kolej).

the SŽ network, the German operator withdraw the 180 series from regular service in December 2014. A single unit (180 014) was donated to a Weimar museum, 2 were disposed of and 16 were purchased by the Czech operator TSS Cargo (Traťová strojní společnost) of Ostrava (Fig. 29), which also leases 180 series locomotives to other operators (IDS Cargo, LokoTrain and others).

Figures 30–37 show bogies of selected locomotive series, and Figures 38–45 show pantographs.

Fig. 29. 180 015 (TSSC) at Přerov station, Czechia (17 May 2017) [photo by PetrS]


Fig. 30. A 362 series locomotive bogie [photo by M. Graff]


Fig. 31. A 163 series locomotive bogie [photo by M. Graff]


Fig. 32. A 210 series locomotive bogie [photo by M. Graff]


Fig. 33. A 151 series locomotive bogie [photo by M. Graff]


Fig. 34. A 131 series locomotive bogie [photo by M. Graff]

Fig. 35. A 361 series locomotive bogie [photo by M. Graff]


Fig. 36. A 263 series locomotive bogie [photo by M. Graff]


Fig. 37. A 350 series locomotive bogie [photo by M. Graff]


Fig. 38. A 263 series locomotive pantograph [photo by M. Graff]

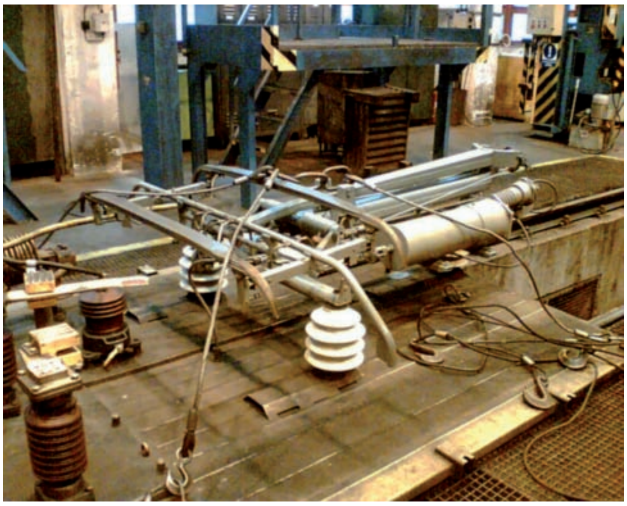
Fig. 41. A 371 series locomotive pantograph [photo by P. Větříšek]


Fig. 39. A 131 series locomotive pantograph [photo by M. Graff]

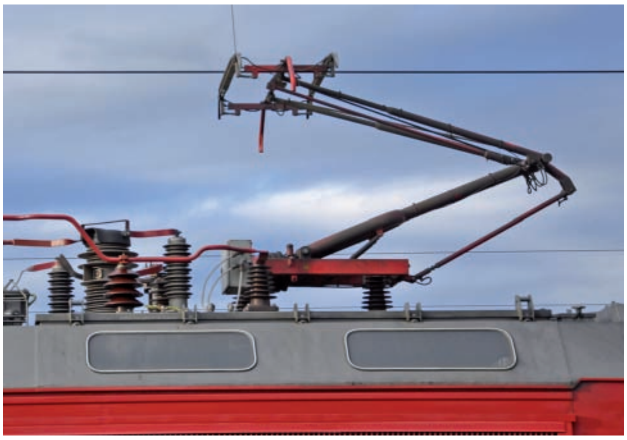
Fig. 42. A 361 series locomotive pantograph [photo by M. Graff]


Fig. 40. A 210 series locomotive pantograph [photo by M. Graff]


Fig. 43. A 163 series locomotive pantograph [photo by M. Graff]

Fig. 44. A 151 series locomotive pantograph [photo by M. Graff]

Fig. 45. A 350 series locomotive pantograph [photo by M. Graff]

For technical and statistical details of selected locomotives manufactured by Škoda and described in the article, see Tables 4–7.

7. Conclusion

Over the years, Škoda has shown that it can produce modern locomotives well suited to user requirements. Despite initial difficulties with pulse start-up, the Pilsen-based manufacturer has proven that its vehicles are reliable. Škoda's most recent innovation in terms of new-generation rolling stock is type 109E, a three-system (3 kV DC, 15 kV 16.7 Hz, 25 kV 50 Hz) high-powered locomotive, ordered by the Czech and Slovak railways (and also tested in Poland in 2012 on the Węglewo test track). Škoda locomotives operate on the rail network of the Polish operator PKP as well. Indeed, it was the successful EU05 series vehicles purchased from Czechoslovakia in the 1960s that allowed the PKP to become familiar with the specifics of electric traction. Today, second-generation Škoda locomotives not only enter PKP PLK's network from Czechia, Slovakia, and Germany but also run scheduled freight and passenger (including qualified) trains on PLK's network under agreements on liberalization of access to railway infrastructure within the EU member states.

Czechoslovak, Czech and Slovak rolling stock designation system

The ČSD rolling stock designation system was changed on 1 January 1988; e.g., the earlier designation E 458.0 was changed to the current 110. Electric locomotive designations were as follows:

- letter E[12] – 3 kV DC vehicles,
- letter S[13] – 25 kV 50 Hz vehicles,
- letters ES – two-system vehicles (3 kV DC + 25 kV 50 Hz / 3 kV DC + 15 kV 16.7 Hz / 25 kV 50 Hz +15 kV 16.7 Hz).

Following the introduction of the new locomotive designation system, the designations are as follows:

- 100 to 199 – 3 kV DC vehicles,
- 200 to 299 – 25 kV 50 Hz vehicles,
- 300 to 379 – two-system vehicles (3 kV DC + 25 kV 50 Hz / 3 kV DC + 15 kV 16.7 Hz / 25 kV 50 Hz +15 kV 16.7 Hz),
- 380 to 399 – tri-system vehicles (3 kV DC + 15 kV 16.7 Hz + 25 kV 50 Hz).

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[12] E – for "electric".
[13] S – for "střídavý" (alternating).

Table 4

Statistical data on selected Škoda electric locomotives

Type	Designation ČSD / DR / FNM / BDZ	Current operator	Current designations	Years of production or start of operation	Number of units produced / upgraded*	Number of ČD locomotives	Number of ZSSK locomotives	Number of TSS locomotives (former DB)	Number of FNM / RJ locomotives	Number of BDZ locomotives
33E **78E**	E 458.0	ČD, ČD, ZSSK	110 111	1971–1973 1981–1982	52 35	6 30	2 –	– –	– –	– –
33E	E 426	ČD	113	1973	6	3	–	–	–	–
58E	E 479.1	ZSSK	131	1980–1982	50	–	50	–	–	–
65E **65Em**	E 499.2 –	ČD	150 151	1978 1994	27 13*	12 13	– –	–	– –	– –
98E	E 499.4	ČD, ZSSK	162	1991	60	20	8	–	–	–
71E **99E** **no data**	E 499.3	ČD, ZSSK	163 163 163.2	1984–1986 1991–1992 1993–1994	120+28*	75	13	– –	– –	– –
51E	S 458.0	ČD, ZSSK	210	1972–1984	74	24	6	–	–	–
	61 (BDZ)	BDZ	61	1994	20	–	–	–	–	20
73E 1-3	S 499.1	ČD	242	1975–1981	86	82	–	–	–	–
68E	43	BDZ	43	1971–1984	56	–	–	–	–	31
68E1	44	BDZ	44	1975–1981	89	–	–	–	–	43
68E1	45	BDZ	45	1982–1983	60	–	–	–	–	36
70E	S 499.2	ČD, ZSSK	263	1984 1988	12	2	10	–	– –	– –
55E	ES 499.0	ZSSK	350	1973–1975	20	–	18	–	–	–
69Er	–	ČD, ZSSK	362	1990 1993–1994	100*	80[1]	20[1]	–	– –	– –
69E **71Em** **no data** **no data**	ES 499.1 – – –	ČD, ZSSK ČD ZSSK ZSSK	363 363.5 361.0 361.1	1980–1990 2011– 2011– 2012–	181 30* 5* 23*	50 30 – –	9 – 5 23	– – – –	– – – –	– – – –
76Em	–	ČD	371	1996–2000, 2004	7*	7[2]	–	–	–	–
80E **76E**	ES 499.2	ČD	372	1988 1991	15	9	–	–	–	–
80E **76E**	230 (DR) / 180 (DB)	DB / DR (1991–2014), TSS Cargo (2014–)	180	1988 1991	1 19[3]	– –	– –	1 16	– –	– –
99E	E 630 (FNM)[4]	FNM (1995–2010), RJ (2010–)	E 630 162	1991–1992	9	–	–	–	9	–

[1] When converting locomotives 363 to 362, ČD retained the existing inventory numbers and ZSSK numbered the locomotives starting from number „1"; [2] 1 unit was received from DB; [3] 1 unit was transferred to ČD; [4] Ferrovia Nord Milano S.p.A. (FNME), Italy, operated from 1992 to 2010, sold to the RegioJet (Czech Republic); [authors' own elaboration – tables 4–7].

Table 5

Technical data of selected Škoda electric locomotives

Current designations	Axle arrangement	Voltage	V_{max} [km/h]	Total length [mm]	Max. tractive force [kN]	Weight [t]	Max. Pressure of the wheelset on the rails [kN]
110 **111**	Bo'Bo'	3 kV DC	80	14,400	160 186	72.0	18.0
113	Bo'Bo'	1.5 DC	50	14,400	160	64.0	16.0
131	2 · Bo'Bo'	3 kV DC	100	34,540	350	169.0	21.1
163	Bo'Bo'	3 kV DC	120	16,800	258 300	85.0	21.3
162 **163.2**	Bo'Bo'	3 kV DC	140 120	16,800	258 285/300	85.0	21.3
150 **151**	Bo'Bo'	3 kV DC	140 160	15,500	227	82.5	20.6
350	Bo'Bo'	3 kV DC; 25 kV 50 Hz	160	15,500	210	88.0	22.0
210	Bo'Bo'	25 kV 50 Hz	80	14,400	164	72.0	18.0
242	Bo'Bo'	25 kV 50 Hz	120	16,440	240	84.0	21.0
43 (BDZ)	Bo'Bo'	25 kV 50 Hz	130	16,440	240	84.0	21.0
44 (BDZ)	Bo'Bo'	25 kV 50 Hz	130	16,440	no data	87.0	21.8
45 (BDZ)	Bo'Bo'	25 kV 50 Hz	110	16,440	no data	87.0	21.8
263	Bo'Bo'	25 kV 50 Hz	120	16,800	250 300	84.0	21.0
361.0 **361.1**	Bo'Bo'	3 kV DC, 25 kV 50 Hz	140 160	16,800	260	86.0	21.5
362	Bo'Bo'	3 kV DC; 25 kV 50 Hz	140	16,800	260	87.0	21.8
363	Bo'Bo'	3 kV DC; 25 kV 50 Hz	120	16,800	260	87.0	21.8
363.5	Bo'Bo'	3 kV DC; 25 kV 50 Hz	120	16,800	300	88.0	22.0
372 **371**	Bo'Bo'	3 kV DC; 15 kV 16.7 Hz	120 160	16,800	243	84.0	21.0
180 (DB)	Bo'Bo'	3 kV DC; 15 kV 16.7 Hz	120	16,800	300	84.0	21.0
E 630 (FNM) **162 (RJ)**	Bo'Bo'	3 kV DC	120 140	16,800	300 258	80.0	20.0

Table 6

Technical data of selected Škoda electric locomotives, cont.

Current designations	Continuous electric motor power [kW]	Locomotive continuous power [kW]	Traction motor starting	ED (resistance) brake power [kW]	Transmission ratio
110 **111**	200 200	800 760	R thyristor	no data no data	3.48
113	200	400	R	no data	no data
131	560	4480	R	no data	2.70
162 **163.2**	900	3,480	thyristor	3,000	3.04 3.52
163	900	3,480	thyristor	3,000	3.52
150 **151**	1,000	4,000	R	3,600	2.44 2.16

Table 6 cont.

Current designations	Continuous electric motor power [kW]	Locomotive continuous power [kW]	Traction motor starting	ED (resistance) brake power [kW]	Transmission ratio
350	1,000	4,000	R	3,600	2.16
210	220	880	thyristor	no data	4.06
242	800	3,080	high-voltage control	–	3.2
43 (BDZ)	800	3,040		2,900	3.348
44 (BDZ)	800	3,140		no data	3.95
45 (BDZ)	800	3,140		no data	3.348
263	900	3,060	thyristor	3,000	3.52
361.0 **361.1**	900	3,200 (AC) 3,600 (DC)	IGBT	no data	3.52 no data
362	900	3,060 (AC) 3,480 (DC)	thyristor	3,000	3.04
363.5	925	3,700 (AC/DC)	IGBT	no data	3.52
363	900	3,060 (AC) 3,480 (DC)	thyristor	3,000	3.52
372 **371**	900	3,080	R (3 kV DC) / high voltage control (15 kV 16.7 Hz)	2,200	3.52 2.64
E 630 (FNM) **162 (RJ)**	900	3,480	thyristor	3,000	3.52 3.04
180 (DB)	900	3,080	R (3 kV DC) / high voltage control (15 kV 16.7 Hz)	2,200	3.52

Table 7

Statistical data on selected Škoda electric locomotives, cont

Operator	Series (current designa-tions)	Number of locomotives produced/ upgraded*	Number of locomotives in service	Stationing			
				ČD + ČD Cargo	ZSSK +ZSSK Cargo	TSS Cargo	Regio-Jet
ČD / ZSSK	110	52	8	Ostrava – 3, Praha Vršovice – 2, Ústí nad Labem – 1. TOTAL: 6	Košice – no data Žilina – no data TOTAL: 2	–	–
ČD	111	35	30	Bohumín – 2 Hradec Králové – 2 Ostrava – 6, Praha Vršovice – 8, Ústí nad Labem – 12. TOTAL: 30	–	–	–
ČD	113	6	3	Tábor – 3	–	–	–
ZSSK	131	50	50	–	Spišská Nová Ves – 50	–	–
ČD	150	27	12	Praha Vršovice – 12	–	–	–
ČD	151	13*	13	Bohumín – 13	–	–	–
RegioJet	162	9*	9	–	–	–	no data
ČD / ZSSK	162	60	28	Česká Třebová – 7, Děčín – 12, Praha Vršovice – 1. TOTAL: 20	Žilina – 8	–	–

ČD / ZSSK	163+163.2	120+28*	88	Bohumín – 8, Česká Třebová – 9, Děčín – 16, Olomouc – 6, Ostrava – 12, Praha Vršovice – 6, Ústí nad Labem – 18. TOTAL: 75.	Košice – 9, Žilina – 4. TOTAL: 13	–	–
TSS Cargo	180	19 / 7*	7	–	–	Hulín – 7	–
ČD / ZSSK	210	74	30	České Budějovice – 15, Plzeň – 2, Tábor – 7. TOTAL: 24	Bratislava východ – no data Zvolen – no data TOTAL: 6	–	–
ČD / ZSSK	263	12	12	Brno Maloměřice – 2	Bratislava – 10	–	–
ZSSK	350	20	18	–	Bratislava – 18	–	–
ZSSK	361.0 361.1	5* 23*	5 23	–	Bratislava – 5 + 23. TOTAL: 28	–	–
ČD / ZSSK	362	100*	100	Brno Maloměřice – 38, Plzeň – 42. TOTAL: 80	Bratislava – 19, Bratislava východ – 1. TOTAL: 20	–	–
ČD / ZSSK	363	181	59	Ostrava – 30, Plzeň – 3, Ústí nad Labem – 17. TOTAL: 50	Bratislava – no data Bratislava východ – no data TOTAL: 9	–	–
ČD	363.5	30*	30	České Budějovice – 30	–	–	–
ČD	371	7*	7	Praha Vršovice – 7	–	–	–
ČD	372	15	9	Ústí nad Labem – 9	–	–	–

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Credit for collaboration and my thanks to Ing. J. Pernička (Railvolution), Ing. P. Štefek (DB Cargo Czechia) and M. Eng. D. Kalinowski (Pesa Bydgoszcz, Ph. D. student at the Institute of Fundamental Technological Research, Polish Academy of Sciences, Warsaw).